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MASS ANALYSIS OF NEUTRAL PARTICLES AND IONS RELEASED DURING
ELECTRICAL BREAKDOWNS ON SPACECRAFT SURFACES

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MASS ANALYSIS OF NEUTRAL PARTICLES AND IONS RELEASED DURING ELECTRICAL BREAKDOWNS ON SPACECRAFT SURFACES

1. ABSTRACT

Charging of insulating surfaces and the resulting electrical breakdowns are known to have been responsible for numerous malfunctions of orbiting spacecraft. Both theoretical and experimental studies of charged-particle fluxes from breakdown events are now being made in several laboratories.

The present research broadens the attack on this problem to include neutral particles (molecules and molecular clusters) and specifically to develop methods of measuring the mass and velocity distributions of such particles.

The design and construction of the specialized mass spectrometer required for this work was completed at the end of January 1981. Tests at Penn State were entirely satisfactory.

Subsequent tests in the Tenney vacuum chamber at the NASA Lewis Research Center disclosed a problem involving deterioration of the ion source and detector performance over periods as short as thirty minutes. The mass spectrometer has since been restored to normal operation by extensive cleaning and rebuilding. The reassembled instrument has been operating satisfactorily for many months in the original test chamber at Penn State, where all further experiments will be carried out.

Samples of several types and thicknesses of metal-backed insulating films were obtained from John V. Staskus at the NASA Lewis Research Center. The initial experiments have concentrated on observations of neutral particles released from metal-backed Teflon and Kapton films.

Promising results have been obtained with an insulation breakdown initiation system based on a movable contact touching the insulated surfaces. A variable-energy high-voltage pulse is applied to the contact. The resulting surface damage sites can be made similar in size and shape to those produced by a high voltage electron beam system operating at similar discharge energies. The point discharge apparatus has been used for final development of several different high-speed recording systems and for measurements of the composition of the materials given off by the discharge. An additional advantage of this technique is that, by progressively rotating or moving the sample beneath the contact, the observed gas bursts can be correlated with actual discharge sites

left behind on the sample, which can then be removed and observed under an optical or electron microscope.

Results with this apparatus show evolution of large amounts of heavy fluorocarbon fragments from discharges through Teflon FEP, while discharges through Kapton produce mainly very light hydrocarbon fragments at masses below about 80 a.m.u.

Construction of a miniaturized electron beam charging system, similar in principle to that used at NASA Lewis Research Center but arranged to be structurally compatible with the Penn State test chamber, has been completed.

2. INTRODUCTION TO THE PROBLEM

Spacecraft charging in geomagnetic substorms often leads to large changes in potential of spacecraft surfaces relative to space plasma potential. An additional source of localized charging of spacecraft surfaces occurs in the interaction of high-voltage solar arrays with the charge exchange plasma generated by ion thrusters. In either case the resultant potential differences may reach several kilovolts. The charging may lead to large potential gradients across dielectrics used on the spacecraft surfaces or used to insulate one part of the spacecraft from another.

Discharges across spacecraft dielectrics may produce spurious electromagnetic signals. Discharges may also degrade thermal protective films, contaminate optical surfaces, and cause direct structural damage to the dielectrics. Laboratory tests indicate the possibility of degrading other insulators if metallic vapors are emitted from the discharge, or of forming extremely thin insulating layers on conductors which can then charge enough to modify critical electrostatic field distributions near charged-particle detection equipment. In general there will be a large and almost instantaneous release of both neutral and charged particles from the site of a breakdown event. Hundreds of charging-induced anomalies were identified in more than twenty spacecraft between 1971 and 1976.

Because of the absence of existing data on the composition of the neutral and ion fluxes from dielectric breakdown events, mass spectrometric analyses of these fluxes are particularly important.

Mass analysis of particles from an electrical breakdown event involves a particularly difficult set of constraints. The event occurs essentially at a point in space and at an instant in time. The exact position and timing of the event are not known in advance, although they can be influenced to

some extent. The event produces a swarm of neutral molecules, molecular clusters and ions of different masses which presumably radiate from the breakdown site over a wide range of speeds and directions. At a distance greater than a few cm from the breakdown site the particle number density is likely to be quite low and falling rapidly because of both speed variations and angular dispersion. The expanding gas and ion burst will pass any given point in a time much shorter than the time taken for any conventional mass spectrometer to scan once through its mass range.

The difficult experimental conditions listed above make it essential to use a mass spectrometer in which a maximum amount of output data can be obtained in the shortest possible time. This effectively limits the choice of spectrometer types to those in which all of the ions leaving the ion source become part of a recorded output signal. For reasons discussed in the original proposal, it has been decided that a time-of-flight mass spectrometer offers the most cost-effective approach.

A general description of the time-of-flight mass spectrometer designed and constructed for this work has been given in preceding reports and will not be repeated here. A detailed diagram of the instrument and its pumping system is shown in Fig. 1, and details of the point-contact surface breakdown apparatus are given in Fig. 2.

3. PROGRESS (for period 4 September 1982 - 3 March 1982)

Note: The Principal Investigator was on sabbatical leave at the Jet Propulsion Laboratory, Pasadena, CA during part of this period.

A. Reduction of Background Gas Level

After the mass spectrometer had returned from tests in the Tenney vacuum chamber at NASA Lewis Research Center it showed a peak at mass 149 in its mass spectrum which had not been present before. Such a peak is usually a sign of hydrocarbon contamination by mechanical pump oil.

Cleaning and rebuilding of the ion source and detector assemblies reduced but did not eliminate the unwanted mass peak. It was desirable to eliminate it (and also small peaks at masses 28 and 32 resulting from a minor air leak) before continuing with tests on the breakdown of polymer films in order to improve the signal-to-background ratio.

Additional cleaning of the mass spectrometer housing, careful polishing of sealing surfaces, and addition of a cold trap improved the total pressure by a factor of about three and eliminated the interfering mass peaks. The new background mass spectrum is shown in Fig. 3.

B. Direct Contact Breakdown Experiment

An insulation breakdown initiation system based on a smooth movable platinum contact touching the insulating surface was constructed during the previous reporting period. Development has continued during the present period. A variable-energy high-voltage pulse is applied to the contact. The resulting surface damage sites can be made similar in size and shape to those produced by a high-voltage electron beam system operating at similar discharge energies. An additional advantage is that, by progressively rotating the sample beneath the contact, the observed gas bursts can be correlated with actual discharge sites left behind on the sample, which can then be removed and observed under an optical or electron microscope.

C. High Speed Recording Using Photographic and Electronic Storage Techniques

A review has been made of a number of the high speed recording techniques applicable to mass spectrometry. This work has formed the basis of a thesis by J. Dormer. Some of the techniques have already been used in this work. An example is the intensity - modulated raster display, the basic principle of which is shown in Fig. 4. Another is the Standard Multitrace raster display, (Fig. 5) in which groups of conventional mass spectra (typically 1-16 per group) are superimposed upon one another, after which the display moves upwards for display of the next group.

More sophisticated techniques are being developed which improve the accuracy of peak height measurements. They will be discussed in the next report.

D. New Polymer - Film Breakdown Data

The apparatus described in (B) and (C) above has been used for further measurements on the breakdown of Teflon FEP samples. The results confirm the breakdown of the Teflon polymer structure in a way very different from the published results for thermal breakdown. It should be noted, however, that the thermal data were for the slightly different Teflon TFE. The electrical breakdown data were discussed in the previous report and are summarized in Table I. Far more of the heaviest fragments were observed than are present in the mass spectrum of the heaviest fluorocarbons for which published data are available (C_6F_{14}), suggesting that very large fragments, of mass $>>350$ amu, were leaving the Teflon surface during the discharge.

Fig. 6 shows the chemical structure of Teflon and Kapton. The origins of many of the observed fragment ions (formed in the mass spectrometer ion source by electron bombardment of even larger polymer fragments released by the discharge) are obvious.

After completion of the Teflon tests, a 50 micron Kapton film with metal backing was installed in the apparatus and a new series of breakdown measurements was begun. Results were very different. The Kapton produced only light fragments, giving rise to mass spectra containing mainly masses 44, 28 and 15. Examples are shown in the intensity modulated spectrum of Fig. 7 and the multitrace raster display in Fig. 8. Preliminary identification of the mass peaks from details of the minor fragment peaks suggest that mass 44 is CO_2^+ and C_3H_8^+ ; mass 28 is CO^+ and C_2H_4^+ , and mass 15 is CH_3^+ . It should be noted that Kapton contains a substantial amount of oxygen.

In general breakdown voltages were higher for a given thickness of Kapton than with Teflon.

E. Miniaturized Electron Beam Charging System

Construction is nearing completion on a miniaturized electron beam charging system similar in principle to that used at NASA Lewis Research Center but rearranged to be structurally compatible with the Penn State test chamber. It uses a small commercial electron gun modified to allow operation at up to 20 Kv. Test results will be given in the next report.

4. SEQUENCE OF FUTURE WORK

- A. Final development of high-speed recording techniques.
- B. Tests on Mylar samples.
- C. Design and construction of angled adapter to provide line-of-sight path for discharge fragments into the ion source while blocking the line-of-sight path into the ion detector.
- D. Completion of electron gun testing and integration with existing apparatus.
- E. Experiments using mass spectrometer/electron gun combination to study composition of neutral particles.
- F. Measurement of angular dependence of neutral composition.
- G. Modification of basic mass analyzer for ion studies.
- H. Final reports and publications.

5. PUBLICATIONS

1. B. R. F. Kendall and F. A. S. Schwab, "Production of Pulsed Electric Fields Using Capacitively Coupled Electrodes," Review of Scientific Instruments 51, 1560 (1980).
2. B. R. F. Kendall, "Vacuum Applications of Metal Foams," Journal of Vacuum Science and Technology 17, 1385 (1980).
3. B. R. F. Kendall, "Cyclic Pressure Fluctuations Above Rotary Pumps and Their Effects on Pumping Speed Measurements," Journal of Vacuum Science and Technology 19, 109 (1981).
4. B. R. F. Kendall, "Anaerobic Polymers as High-Vacuum Leak Sealants," Journal of Vacuum Science and Technology 20 (2), 248 (1982)
5. B. R. F. Kendall, "Obtaining Pressures in the 10^{-5} Pa Range with Oil-Sealed Rotary Vacuum Pumps," Journal of Vacuum Science and Technology 21, 886-890 (1982).
6. S. M. Danziger, B. R. F. Kendall, and J. Dormer, "Pressure Pulsations Above Turbomolecular Pumps," Journal of Vacuum Science and Technology 21, 893-895 (1982).

6. THESES COMPLETED

S. M. Danziger, "Electron Gun Modeling with an Electrolytic Tank," M. S. Thesis, March 1981.

P. Desai, "High-Frequency Integrated - Circuit Preamplifiers", M.S. thesis, March 1983.

J. Dormer, "Recording Very Fast Changes in Gas Composition", M.S. thesis, March 1983.

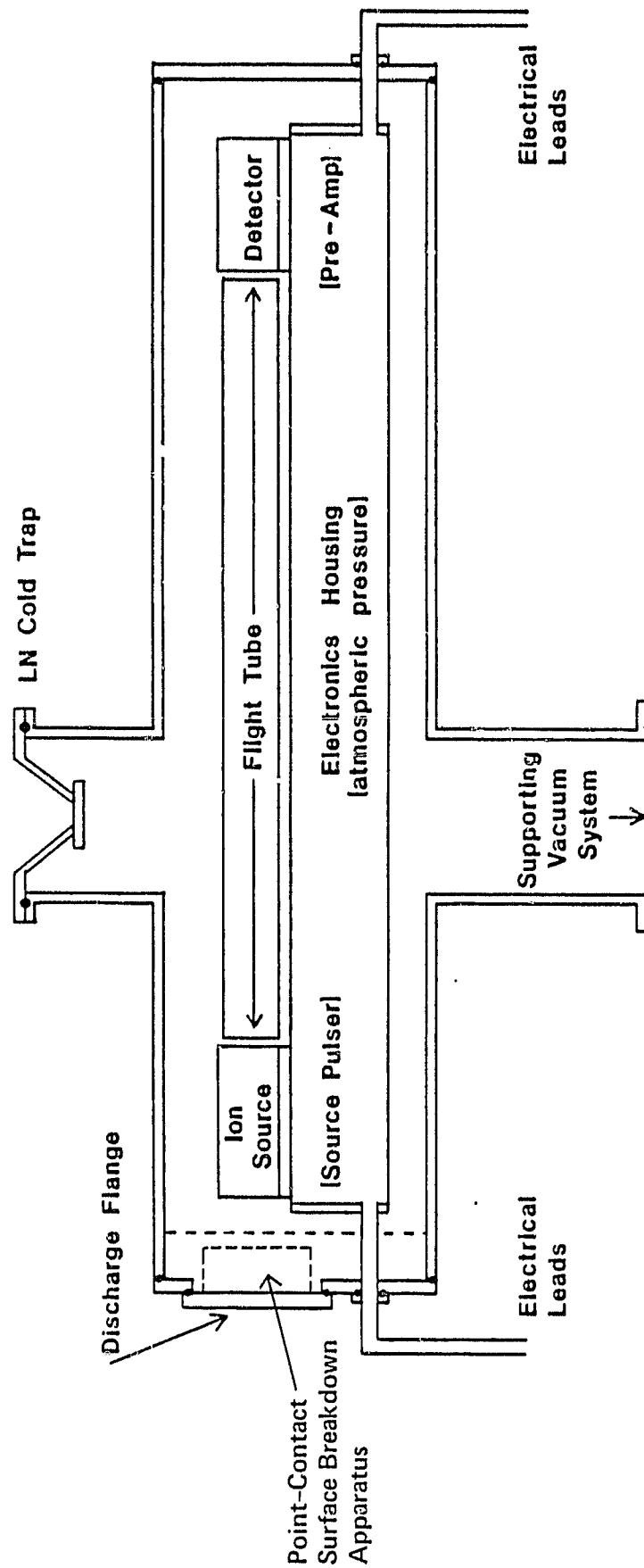


Figure 1. Physical Layout of the TOFMS

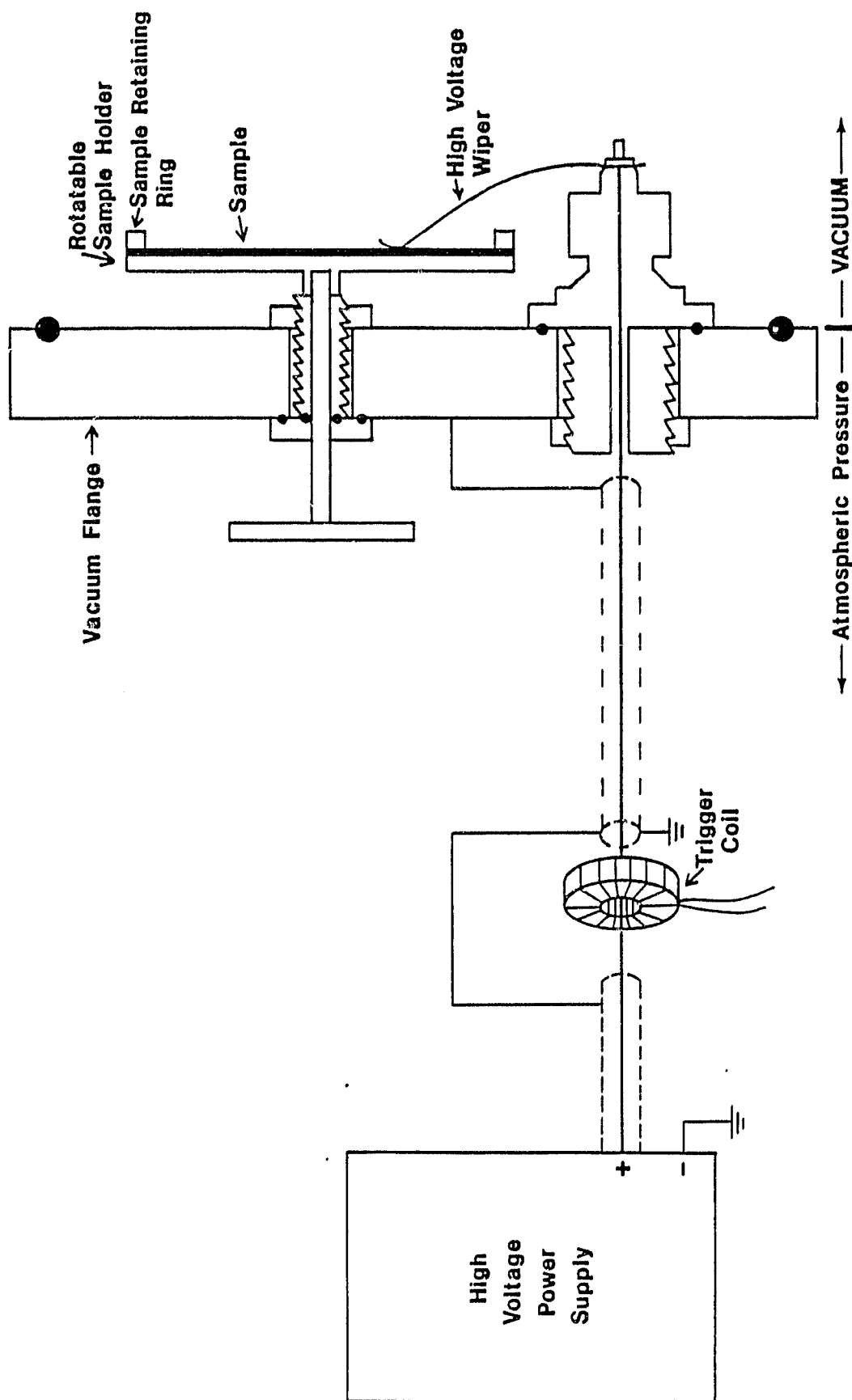


Figure 2. Point-Contact Surface Breakdown Apparatus

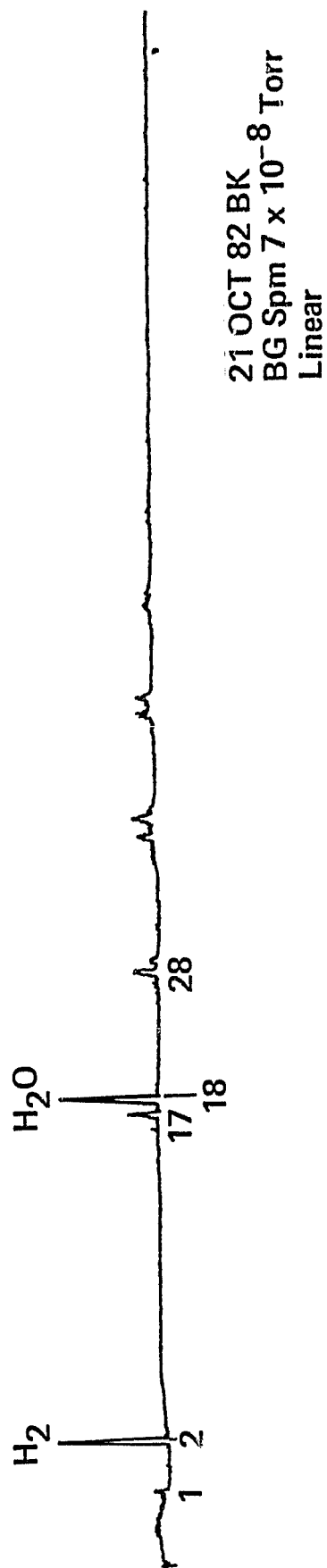


Figure 3. Mass Spectrum of Background Gases in Vacuum Chamber

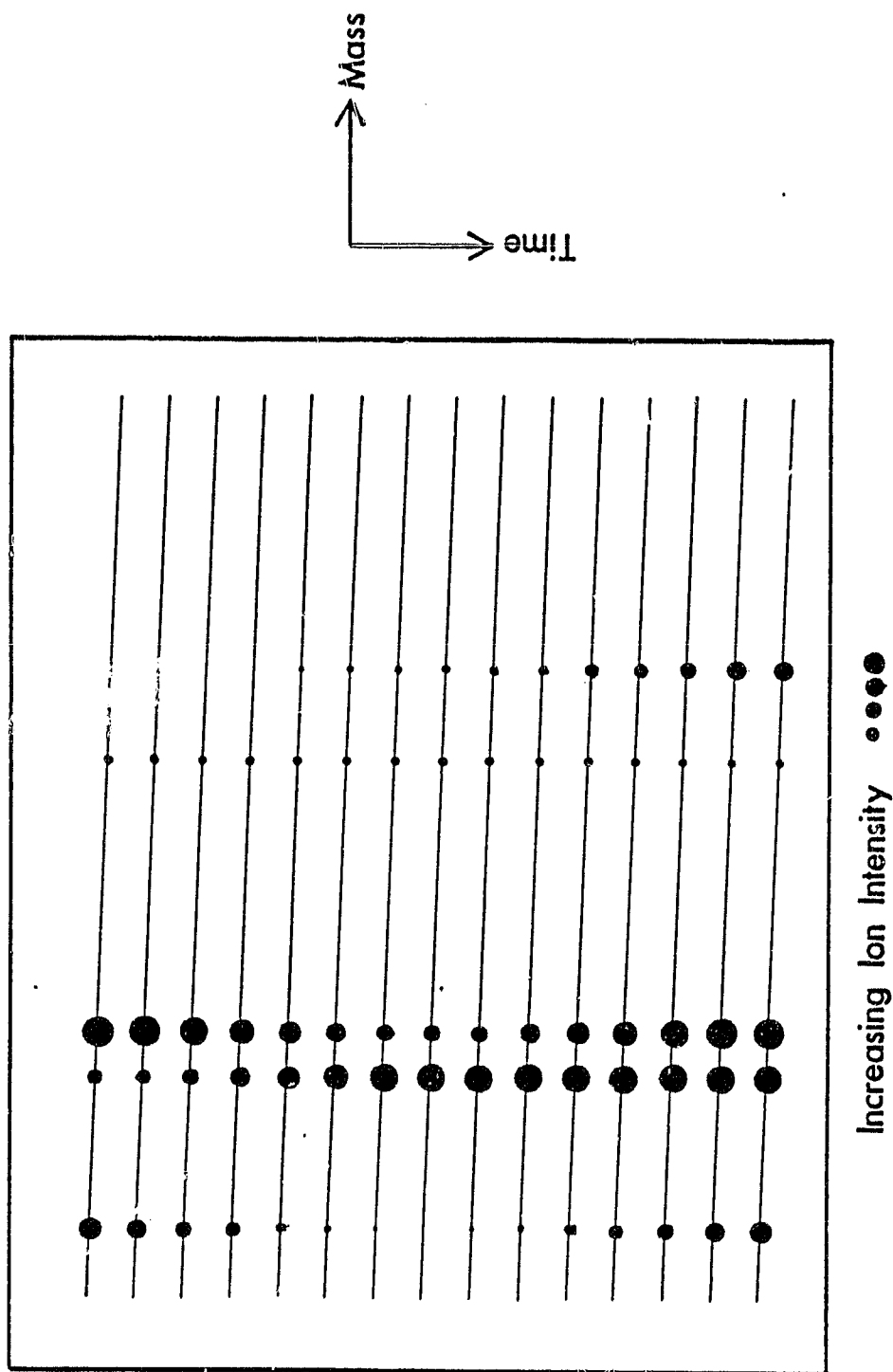
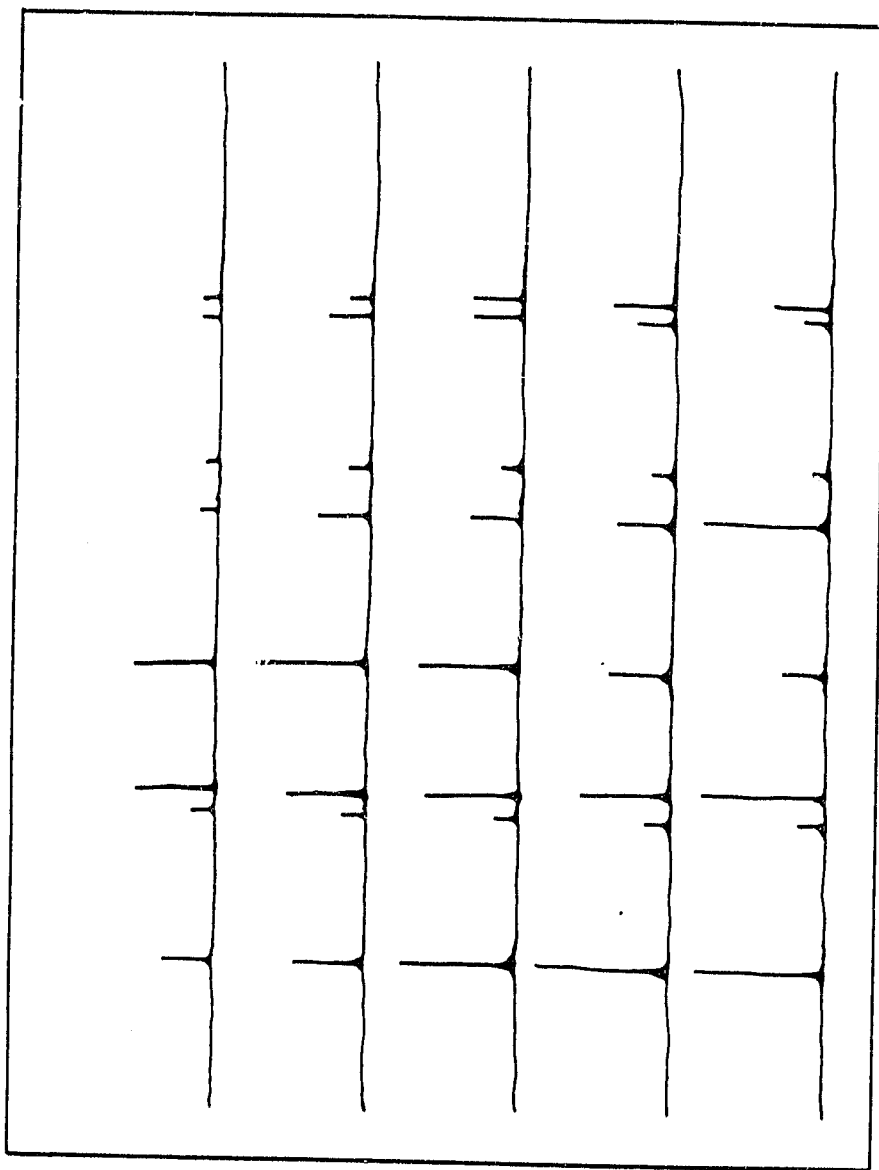


Figure 4. Intensity-Modulated Raster Display-Basic Principle

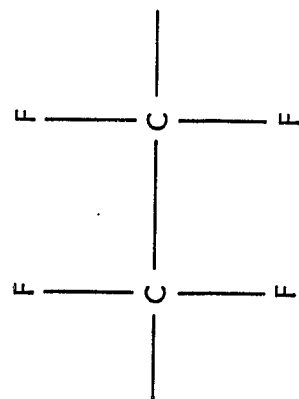


Time →
Mass →

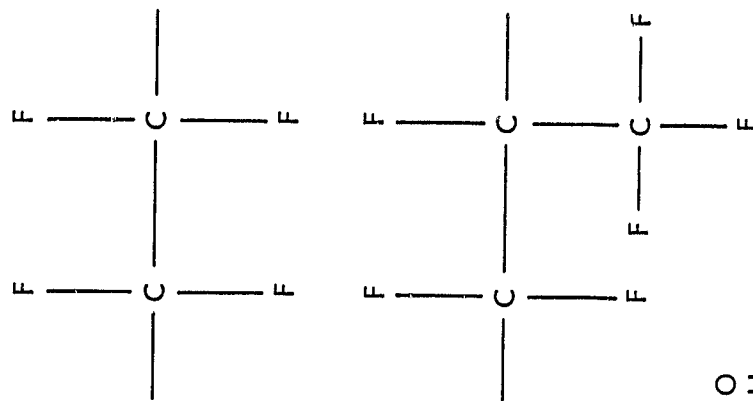
Figure 5. Standard Multitrace Raster Display

Table I Ions produced by electron bombardment ionization of Teflon fragments.
 Fragments produced by 16 Kv breakdown of 50 micron Teflon FEP film.
 Probe: 1 mm Platinum wire. In order of decreasing abundance.

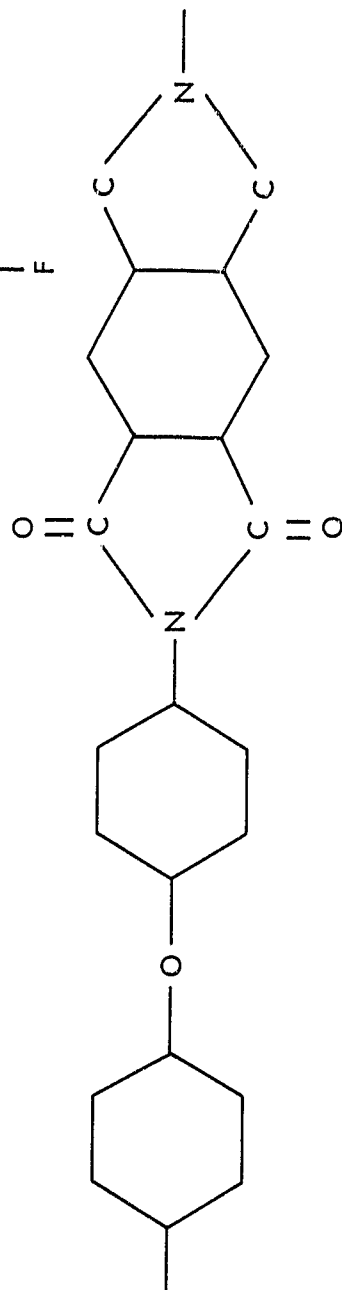
CF_3^+
C_2F_5^+
C_3F_5^+
C_3F_7^+
C_4F_7^+
C_2F_4^+
C_3F_3^+
C^+
C_4F_9^+
C_5F_9^+
--
--



TEFLON TFE



TEFLON FEP: COPOLYMER OF



KAPTON H

Figure 6. Polymer Structures. Hydrogen Bonds Omitted in Kapton Structure for Clarity

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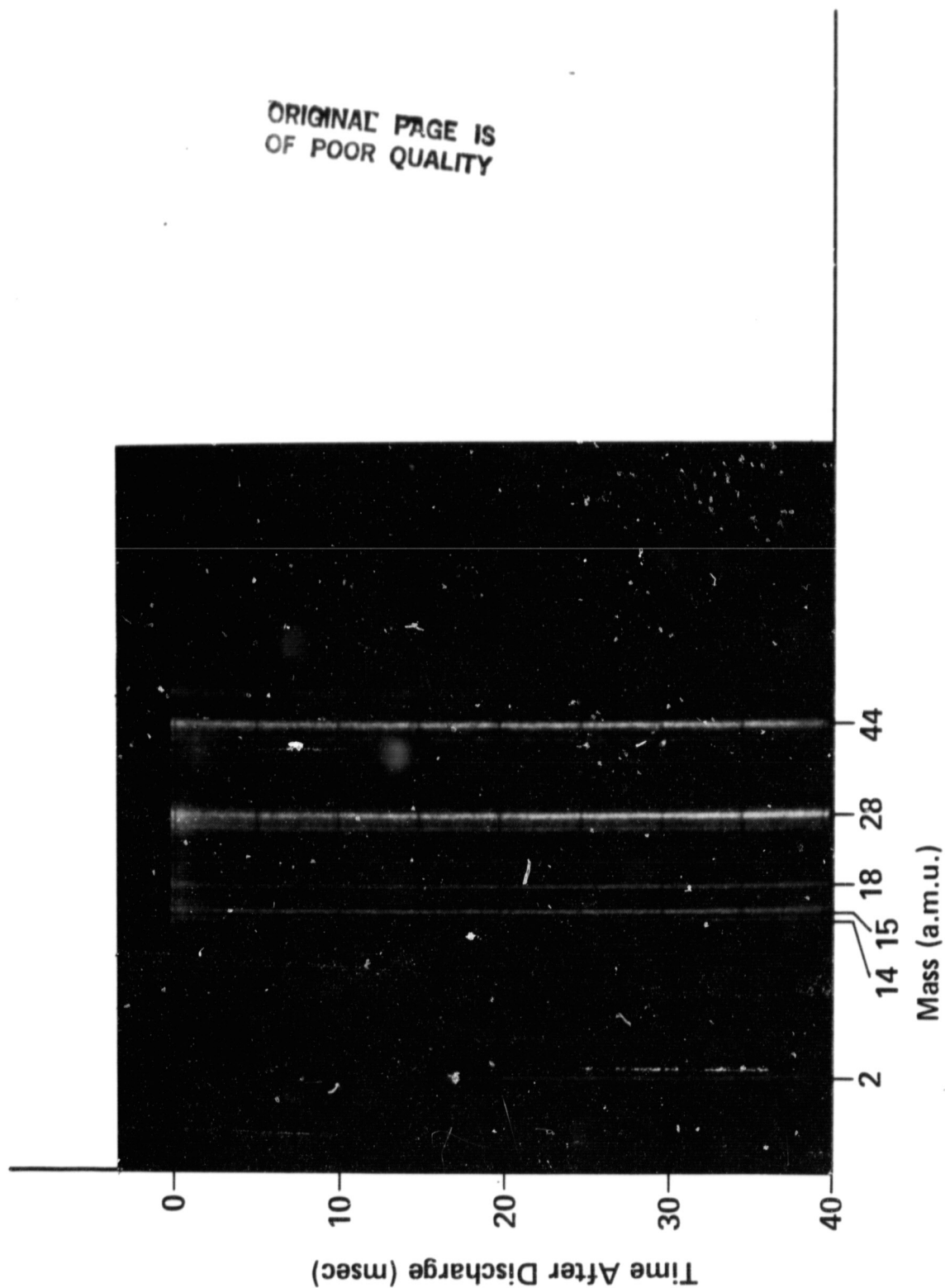


Figure 7. Intensity - Modulated Raster Display for Breakdown of 50 micron Kapton Film at 18 Kv.

Main Peaks 44 (CO_2^+ , C_3H_8^+), 28 (CO^+ , C_2H_4^+), 15 (CH_3^+)

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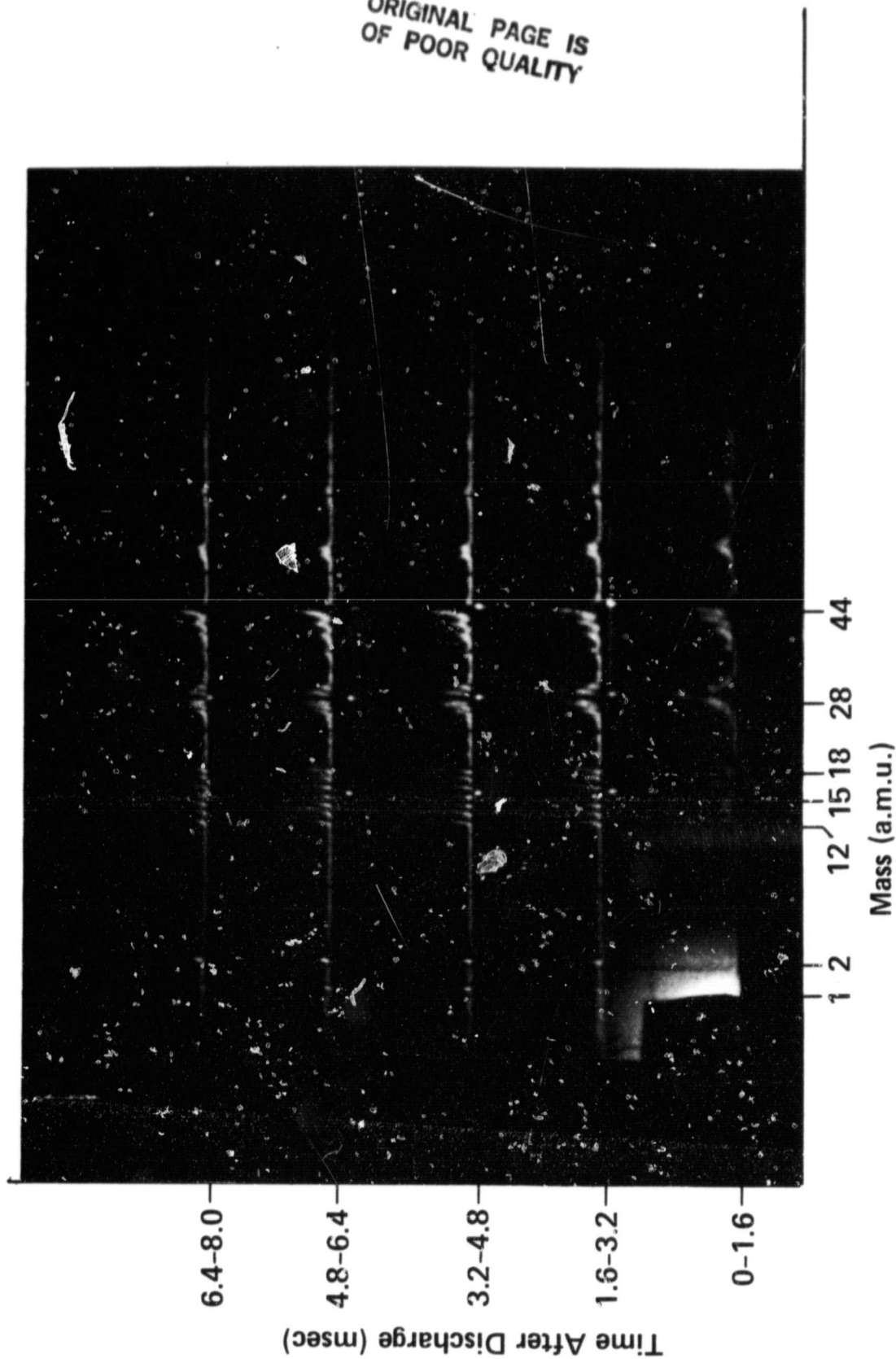


Figure 8. Standard Multitrace Raster Display for 50 micron Kapton Film Breakdown at 18 Kv. Mass Spectrometer Generates 10^4 Spectra/sec. Main Peaks 44 (CO_2^+ , C_3H_8^+), 28 (CO^+ , C_2H_4^+), 15 (CH_3^+)